A 1 Ma sea surface temperature record from the North Atlantic and its implications for the early Human occupation of Britain

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Abstract

The British Quaternary sequence has an exceptionally rich record of Palaeolithic archaeology up to 1 Ma. In this study we re-investigate foraminifera based sea surface temperature (SST) reconstructions from the two marine cores records (ODP Site 980 and M23414), that are most relevant to the climatic history of the British Isles, consequently allowing the evolution of SST over the past 1 Ma to be studied. This is then compared to long-term changes with the British archaeological record in order to understand in greater detail the changing patterns of climatic forcing and the major climatic transitions that were the background environmental drivers against which patterns of early human occupation occurred. These include the Mid-Pleistocene revolution, the Mid-Brunhes Event and changing patterns of isotopic substage complexity. Significantly, however, the SST record indicates that MIS 15 to 13 was characterised by the most prolonged period of consistently warm conditions of the entire 1 Ma interval in the northeast Atlantic. This unique climatic period correlates with the first major proliferation of archaeological sites in northwest Europe. The paper concludes by discussing the significance of these climatic shifts for our understanding of early human occupation in this region.

Key words

Palaeolithic, interglacial-glacial cycles, mid-Brunhes Event, mid-Pleistocene transition

Introduction

The British Quaternary record is one of the best stratigraphically resolved terrestrial archives in the world (Candy et al., 2010). A combination of litho-, morpho- and biostratigraphy, in association with absolute dating techniques, means that it is now possible to routinely correlate interglacial deposits with individual marine isotope stages (MIS)/substages over the past 450,000 yrs (Bridgland, 2000; Schreve, 2001a; Candy et al., 2010; 2014). For the early Middle Pleistocene, 780,000-450,000 yrs, such resolution is not possible, mainly because this time interval lies beyond the range of most dating techniques (Preece and Parfitt, 2000; 2012; Candy et al., 2010; Penkman et al., 2011). However, a combination of biostratigraphy and amino acid racemisation allows interglacial deposits to be separated into discrete stratigraphic groups and correlations with MIS proposed (Penkman et al., 2011; Preece and Parfitt 2012; Candy et al., 2015). As well as allowing important palaeoclimatic questions to be investigated, such as the diversity of Pleistocene interglacial environments, the stratigraphic resolution of the British sequence allows the rich Palaeolithic record of this region to be placed into a chronostratigraphic framework (Penkman et al., 2011). The British Palaeolithic record is particularly long and diverse, with evidence for human occupation going back to ca 1 Ma (Parfitt et al., 2010), with well-documented evidence for clear cultural transitions across this period (see Figure 1 and Ashton et al., 2011; Pettitt and White, 2012). Importantly, it is the robust chronostratigraphic framework of the British terrestrial sequence that allows the timing of these changes/transitions to be established.

A key research question is the relationship between patterns of climate forcing and human occupation in this region (see Parfitt et al., 2005; 2010; Candy et al., 2015). The prevailing model is one of abandonment of the British Isles by early humans during glacial stages and re-occupation during interglacial/temperate episodes (Ashton and Lewis, 2002; Ashton et al., 2011). It is, however, important to highlight that, over the period within which humans have occupied this region a number of major climatic transitions occurred modifying the pattern of glacial/interglacial cyclicity as well as the intensity of both glacial and interglacial periods (Figure 1). During the Early-Middle Pleistocene Transition (EMPT, 1.2 to 0.6 Ma) the periodicity of glacial-interglacial cycles shifted from 41 to 100 kyr, giving rise to very asymmetric climatic cycles with long and severe glacial periods (Pisias and Moore, 1981; Clark et al., 2006; McClymont et al., 2013). A second step occurred at the mid-Brunhes

Event (MBE, ca 450ka), which represents an increase in the magnitude of both glacial cooling and interglacial warmth from MIS 12 onwards (Jansen et al., 1986; Lang and Wolff, 2011; Candy and McClymont, 2013). Sea level reconstructions also indicate higher sea level during peak interglacial conditions after MIS 12 (Elderfield et al., 2012; Spratt and Lisiecki, 2016; Bintanja and van de Wal, 2008). The implication of such climatic transitions is that the characteristics of glacial/interglacial cycles, and, therefore, the potential environmental extremes and stresses, experienced by the earliest humans to occupy northwest Europe may be very different from that which was experienced by human populations in the late Middle or Late Pleistocene (Candy et al., 2011; Parfitt et al., 2005; 2011; Hosfield, 2011).

The major limitation of the British terrestrial record is that there is no long-term, continuous climatic record with which the archaeological sequence can be compared. Consequently, there is a limited understanding of the impact of transitions such as the EMPT and MBE and their environmental implications for early humans. The British terrestrial record is highly fragmented. Interglacial deposits (primarily fluvial channel fills/overbank deposits, short lacustrine sequences and raised beach sediments) typically provide high-resolution records of short intervals of time (Candy et al., 2010). This allows the palaeoenvironment of discrete phases of human occupation to be constructed but provides limited information on the nature of the climate cycles, both their duration and magnitude, which these populations would have experienced (Candy et al., 2015). Consequently, it is difficult to place the Palaeolithic record into the context of long-term climate evolution.

Most studies have compared the British archaeological record to benthic $\delta^{18}O$ records (i.e. Parfitt et al., 2005; 2010), an approach which is clearly problematic because such sequences record an “average” of global ice volume, rather than climate change in any particular region *per se* (or specifically climate change in the region of the British Isles), and are complicated by changes in the temperature of the bottom water masses (Sosdian and Rosenthal, 2009; Elderfield et al., 2012). Whilst the North Atlantic contains numerous sea surface temperature (SST) records the majority of these are not relevant to Britain because either: 1) they do not occur at latitudes and longitudes that are appropriate to the British Isles (Naafs et al., 2012), 2) they reconstruct SST at too low resolution to be relevant to the palaeoclimatic questions that are being asked (Lawrence et al., 2009) and/or 3) they do not span the entirety of the time interval in question, e.g. the last 1 Ma (Wright and Flower, 2002). There is currently no single long, high-resolution record of climate change available that is appropriate to compare the British archaeological record with.

This paper aims to address this issue by re-investigating two records that have the potential to provide a long sea surface temperature (SST) record for the northeast Atlantic. Both Site M23414 (Kandiano and Bauch, 2003) and ODP Site 980 (Wright and Flower, 2002) contain foraminifera that allow mean annual plus winter and summer SSTs to be reconstructed at a resolution of at least 1.2 ka and occur at a latitude and longitude that is relevant to understanding the palaeoclimate of the British Isles. M23414 spans the interval 0-0.5 Ma (Kandiano and Bauch, 2003) whilst the foraminifera record of Site 980 spans 0.5-1 Ma (Wright and Flower, 2002), consequently, the two records allow the last 1 Ma of climate history of this region to be discussed in detail. The paper has two main aims. Firstly, to highlight the main patterns/trends in SST records over glacial/interglacial cycles over the past 1 million years. Secondly, to compare and contrast these patterns with the record of human occupation that is seen in the British terrestrial sequence. The paper concludes by discussing, through an integration of the terrestrial and marine record, the major changes in glacial/interglacial forcing that occurred in this region over the past 1 Ma and the relevance of these changes to understand the environmental drivers of human occupation.

Palaeoclimate in the northeast Atlantic and the early human occupation of northwest Europe

Palaeolithic occupation of northwest Europe

There is abundant evidence for human occupation in northwest Europe, particularly the British Isles (Figure 1), during the early Middle Pleistocene (EMP, 780-450ka)(Parfitt et al., 2005; 2010; Hosfield, 2011; Candy et al., 2015), with more limited evidence for occupation in the late Early Pleistocene (>780ka). In Britain the two oldest sites contain Mode I archaeology (core and flake tools) and are suggested to date to 950-850ka (Happisburgh III) and ca 700ka (Pakefield) on the basis of lithostratigraphy, biostratigraphy, amino acid racemisation (AAR) and palaeomagnetic dating (Parfitt et al., 2005; 2010; Penkman et al., 2011). Whilst there is little debate over these being the oldest archaeological sites in Britain, there has been discussion over their precise age with Westaway (2011) arguing that both sites could be incorporated in a stratigraphic model that places them in separate substages of MIS 15. Less controversial is the presence of a large number of sites containing Mode II archaeology (Acheulian hand axes) in deposits that pre-date the MIS 12 glaciation but, on the basis of biostratigraphic, AAR and geochronological lines of evidence, correlate to late within the EMP, MIS 13 or late MIS 15 (Hosfield, 2011; Candy et al., 2015). From MIS 12 onwards, the evidence for Palaeolithic occupation becomes more abundant and follows a relatively clear pattern of human occupation of the British Isles during warm MIS (interglacials/interstadials) and abandonment during cold MIS (White and Schreve, 2000; Ashton and Lewis, 2002). However, it is now becoming increasingly clear that each interglacial/warm stages has a distinct pattern of human occupation and lithic technology (i.e. White and Schreve, 2000). This pattern persists until the last interglacial/glacial cycle when there is an absence of humans in Britain during MIS 5e but evidence for occupation in the middle of the last glacial (MIS 3) (Ashton and Lewis, 2002; Lewis et al., 2011).

Multi-proxy reconstructions from the earliest occupation sites (1-0.5 Ma) indicate that humans were inhabiting western Europe under a range of environments from interglacial climates that were significantly warmer than modern day Britain, i.e. the "Mediterranean" environment recorded at Pakefield (Parfitt et al., 2005; Candy et al., 2006; Coope, 2006) through to more boreal late interglacial or interstadial climates, i.e. at Happisburgh III and many of the Acheulian sites (Parfitt et al., 2010; Hosfield, 2011; Candy et al., 2015). The age of these sites span key intervals in the long-term evolution of Pleistocene climate (Lisiecki and Raymo, 2005). The interval 1-0.5 Ma, which spans the earliest known appearance of humans in northwest Europe and the widespread adoption of Hand axe technologies, is associated with the EMPT and the increasing strength of glacial cycles (Pisias and Moore, 1981; Lisiecki and Raymo, 2005; Lawrence et al., 2010). In particular, the first evidence of "Hudson Strait" Heinrich(-like) Events in the North Atlantic occurred during MIS 16, indicating a step-change in continental ice sheet extent/dynamics (Hodell et al., 2008; Naafs et al., 2011; Naafs et al., 2013). These early archaeological sites occur prior to the MBE and, therefore, potentially in association with "muted" climate cycles, i.e. "cool" interglacials (Jansen et al., 1986; Lang and Wolff, 2011) with moderate sea level highstands from MIS 19 to 13 (fig. 3) (Elderfield et al., 2012; Spratt and Lisiecki, 2016; Bintanja and van de Wal, 2008).

The implication that the early occupation of northwest Europe occurred in a context of subdued climate cycles, compared to later occupation in the past 400ka, is heavily based on the correlation of the terrestrial record with LR04 (and other benthic $\delta^{18}O$ records) and, hence, a globally averaged signal. It is becoming increasingly evident that transitions such as the EMPT and MBE are spatially variable in both their impact and expression (i.e. Candy and

McClymont, 2013; McClymont et al., 2013) and, in the absence of a long climatic record from the region of the British Isles, it cannot be assumed that global records faithfully represent environmental shifts that early humans in northwest Europe would have been affected by.

Climate records from the North Atlantic

Although a wealth of SST records exist for the North Atlantic (Figure 1) the time interval that they span and the resolution of the palaeoclimate data these contain means that few are appropriate for understanding the long-term climate history of the British Isles (see Candy and McClymont, 2013). As the aim of many of the studies that have generated these records has been the investigation of the MPT, these temperature records either; 1) finish at 0.5 Ma, with no SST data for MIS 12 onwards (Wright and Flower, 2002), or 2) record key climatic intervals at such a low resolution that it cannot be assumed that their thermal regime and climatic structure is reliably characterised (Lawrence et al., 2009).

In the first category are sites such as Site 980 which contain a high resolution (0.6 ka) foraminifera SST record of the interval of the period 0.99-0.5 Ma but no comparable record for the interval 0.5-0 Ma (Wright and Flower, 2002). An example of the second category are sites such as ODP 982 which has an alkenone-based SST record that extends from the present back into the Pliocene (Lawrence et al., 2009). However, the resolution of this record across the last 1 Ma is low (4.5 ka) and is also highly variable. For example, whilst data resolution during MIS 11 is 1.8 ka during MIS 13 it is 7 ka. Whilst high-resolution SST records do exist for the North Atlantic they occur at much lower latitudes than that of the British Isles, these include U1313 with a resolution of 0.4 ka (Naafs et al., 2012), and the high-resolution records generated from a number of cores, extending back into the early Middle Pleistocene, from around the Iberian margin (Martrat et al., 2007; Rodrigues et al., 2011; Rodrigues et al., 2017).

Early studies of Pleistocene SST variability in the North Atlantic spliced different marine core records to produce composite palaeoclimate records spanning the last 1 Ma (Ruddiman et al., 1986; 1989). Whilst such an approach makes a number of assumptions about the relative comparability of long-term ocean circulation at the different sites in question it does allow a more detailed investigation into long-term climate variability to be made. Furthermore, such an approach does allow for the possibility of constructing a long-term, high-resolution SST record for the area of the northern Atlantic relevant to the British Isles as two records are found in this region that, when combined, provide a high resolution foraminifera based SST record for the past 1 Ma. These records are; 1) M23414 (53º 32`N, 20 º 17`W) which spans the interval 0.5-0 Ma and has a SST record at a resolution of 1 sample per 1.2 ka (Kandiano and Bauch, 2003), and 2) Site 980 (55º 29`N, 14º 42`W) which spans the interval 1.0-0.5 Ma and has a SST record at a resolution of 1 sample per 0.7 ka (Wright and Flower, 2002).

Both sites have been used to generate summer and winter SST values using planktonic foraminfera data. Kandiano and Bauch (2003) used three different techniques, the modern analogue technique (MAT), the transfer function technique (TFT) and the revised analogue method (RAM). SST reconstructions by these three approaches were in good agreement with each other but Kandiano and Bauch (2003) focussed on the MAT derived estimates as this approach yielded better calibration results. Wright and Flower (2002) used both the TFT and MAT approaches and whilst there was a general consistency for the climatic structure and magnitude of warmth experienced during MIS 13 and 15 generated by these two techniques this is less true for older parts of the record. For example, the interglacial SST peaks of MIS 19 and 21 are significantly warmer when MAT is applied to the foraminifera data in comparison to the estimates generated by TFT. Both the communality values of the TFT and the dissimilarity scores of the MAT do not suggest that either technique generates temperatures from non-analogue communities in these intervals. However, Wright and Flower (2002) argued that the high temperatures experienced were unlikely to be artefacts of the technique as both MIS 19 and 21 had the sub-polar N. pachyderma (s) near zero for the longest interval at any point in the Site 980 record (1.0-0.5 Ma).

Methodology

This study uses the planktonic foraminifera data from Site 980 and M23414 to re-calculate mean annual SST using the same technique (MAT applied using the MARGO dataset (Kucera et al., 2005)) in order to produce a SST record of the last 1Ma. Although the foraminifera data these reconstructions are based on has been previously published the SST values presented here are entirely new, and slightly different from the previous publications. The chronologies applied to these SST records, as generated by the original authors are based on; 1) tuning the benthic δ^{18}O of the record in question to a previously orbitally resolved benthic record, as is the case for Site 980 (Wright and Flower, 2002), or 2) using sediment reflectance properties of the record in question to tune to a neighbouring record that has been orbitally tuned, as is the case for M23414 (Kandiano and Bauch, 2003). The chronologies presented here are those generated by retuning to the LR04 dataset (Lisiecki and Raymo, 2005). The M23414 record spans 0-505ka, whilst Site 980 spans 513-998ka, consequently a ca 8ka gap exists in the SST record provided by these two records, situated in the middle of MIS 13. In this study this gap is filled by including planktonic foraminifera-based SST data from IODP Site U1314 (Alonso-Garcia et al., 2011a).

Although the two records are separated by ca 200 miles (Figure 2) the SST records are combined as a single composite SST record (Figure 3). This approach is considered valid for two reasons. Firstly, at the present day the summer and winter SST values are identical (Figure 4) at both core sites from surface to a depth of 300 metres (the zone within which planktonic foraminifera exist). Secondly, although no continuous SST record exists for the interval 0-500ka in Site 980, we applied the same technique (MAT and the MARGO dataset) to the foraminifera data of MIS 5 (Oppo et al., 2006) and compare this SST reconstruction to M23414 (Figure 4), and these show that the thermal regime at Site 980 during the last interglacial was identical to that which occurred at M23414. Consequently, although the sites are spatially distinct there is good reason to believe that they experienced similar temperature histories.

SST characteristics of M23414/ODP 980 over the past 1Ma

The late Middle and Late Pleistocene (last ~450 ka)

Figure 3 compares the combined M23414/ODP Site 980 record with both LR04 (0-1000ka) and the EDC temperature anomaly record (0-800ka) (EPICA, 2004; Lisiecki and Raymo, 2005; Jouzel et al., 2007). Detailed interglacial comparisons between the SST record presented here and LR04 and, for MIS 5 to 19, EDC are shown in Figure 5. These comparisons show that a strong consistency exists between the climatic stratigraphy, i.e. the timing and number of warm/cold interludes, of these records. However, the absolute magnitude of glacial/interglacial cycles seen in the North Atlantic is not routinely consistent with that observable in LR04 and EDC. For example, all warm stages of the past 450ka are characterised by clear climatic oscillations at the isotopic substage level with the exception of MIS 11. Both MIS 5 and 9 contain a strong interglacial SST peak early in the warm stage and at least one significant, but cooler, interstadial peak that occurs later, both of which are separated by cooling events. This pattern can be seen in both LR04 and EDC, however, in both cases the magnitude of the interstadial peak is stronger in the northeast Atlantic than in either of these two records. In M23414, for example, MIS 5a is characterised by warmth that is as strong as that experienced in some Middle Pleistocene interglacials but in both EDC and LR04 this interstadial is significantly cooler or characterised by significantly higher $\delta^{18}O$ values than any fully interglacial episode. The absence of a strong interstadial in late MIS 11 is also common to both LR04 and EDC, although a brief SST oscillation occurs in M23414 at ca 375ka. The low resolution of M23414 during late MIS 11 prevents a detailed record of climate change for this period but other high resolution North Atlantic records only show moderate warming events with SST much colder than during MIS 11c (e.g.Stein et al., 2009; Rodrigues et al., 2011). The structure of MIS 7 in M23414 is very similar to that in both LR04 and EPICA, consisting of a short early warm event (7e), a major cooling event (7d) followed by a longer period of warmer temperatures (7c and a) with evidence of only minor cooling within it (7b).

The late Early Pleistocene and early Middle Pleistocene (~1 Ma-450 ka)

The climatic stratigraphy of MIS 13 and 15 in Site 980 are again consistent with that seen in LR04 and EDC. MIS 13 is considered a lukewarm interglacial stage in which ice sheets were relatively large for an interglacial and SST was generally lower than other during interglacials of the last 1 Ma (Lang and Wolf, 2011). MIS 13 warmest intervals in the M23414/ODP Site 980 record show only slightly lower SST than during other interglacials, indicating that even though the ice sheets were larger SST was rather high in the NE Atlantic. This period is characterised by two long warm intervals (of ca 20 ka) separated by a cold interval. Although there is a gap within the MIS 13 record, the temperature maximum occurs in late MIS 13, during the second interstadial event, a feature apparently unique to this interval but common to the record of MIS 13 in many long climatic archives (Lang and Wolff, 2011; Candy et al., 2015). The SST record of MIS 15 is clearly complex comprising multiple warm peaks with SST similar to the interglacials of the last ~450 ka, separated by cold episodes. This pattern is generally consistent with the structure of MIS 15 in LR04 and EDC which both show two major warm events, although some of the warming events in Site 980 show stronger intensity than in LR04 and EDC (Lisiecki and Raymo, 2005; Jouzel et al., 2007). The glacial stage MIS 14 in Site 980 is relatively short compared to all other glacial stages in the record, and characterised by a relatively minor decline in temperatures (Lang and Wolff, 2011). Relatively mild temperatures were also recorded in MIS 8 but during a longer interval. Consequently, although the interval MIS 15/14/13 contains numerous climatic events it represents a prolonged period in which SST oscillated between "mild" and "warm" conditions which is relatively unique in the entirety of the last 1 Ma of SST in the North Atlantic. The SST record of MIS 19 shows a strong interglacial peak early in the warm stage, whilst MIS 17 appears anomalously cool, colder than any other interglacial in the entire record and colder than many of the warm stage interstadials (i.e. MIS 5a) of the past 500ka. MIS 21 and 23 lie beyond the range of EPICA but again show good consistency with their expression in LR04, within which both MIS show that the interglacial peak occurs early in the warm stage. The second half of MIS 21 is cooler but relatively stable in Site 980, mirroring the structure of this warm stage in LR04.

Long-term trends in North Atlantic SST

The M23414/ODP Site 980 record shown in Figure 3 allows observations to be made about long-term climatic trends in the northeast Atlantic. Although the record does not include the start of the MPT (ca 1.2 Ma) it does show that by 1 Ma the coldest phases of glacial cycles were as extreme, and in some cases as long, as those that occurred in the late Middle Pleistocene and onwards. A similar observation can be made in the Iberian Margin SST record of the last 1 Ma (Rodrigues et al., 2017). The lowest SST values recorded in MIS 18, 20 and 22 are as low as those that occurred in MIS 2 and 12. The low temperatures of MIS 20 appear to have persisted for ca 20ka. During this time interval the thermal maxima of interglacials such as MIS 19 and 21 were as warm as those of the Holocene. Consequently, during at least the last 1 Ma, the pattern of extreme glacial/interglacial SST in the NE Atlantic presented the same magnitude as for the late Middle and Late Pleistocene. The record is also informative with regard to the MBE. On the basis of previously published marine and terrestrial records, Candy and McClymont (2013) have suggested that this event is absent in Britain and the North Atlantic. The composite M23414/ODP Site 980 record is relevant to this debate as it supports the suggestion that the MBE is poorly expressed in the North Atlantic, albeit with the caveat that the point at which the two records are joined is the approximate position of the MBE. However, other North Atlantic records like IODP Site U1314 and U1313 and the composite record of the Iberian Margin do not show a clear MBE as well (Alonso-Garcia et al, 2011a; Naafs et al., 2011; Rodrigues et al., 2017).

The pattern of interglacial SST shown in Figure 3 also highlights that the period 0.78-0.45 Ma was, in this region, a period of complex climatic change. That there was little change in the extremity of interglacial/glacial cycles across the MBE is supported by the fact that; 1) the thermal maxima of MIS 13, 15 and 19 were as warm as most post-MBE interglacials and 2) the temperature minima of MIS 16, 18 and 20 were as cool (and as prolonged) as many of the post-MBE cold stages. However, it is also true to say that this record shows a number of subdued climatic cycles, with MIS 17 being a particularly cool interglacial and MIS 14 being a cold stage characterised by a particularly short and moderate glacial maxima. High intensity interglacials clearly occur in the northeast Atlantic prior to the MBE, however, some aspects of the early Middle Pleistocene interval appear to be relatively unique. In particular the period MIS 15-14-13 (ca 0.62 to 0.49 Ma) appears to be relatively distinct in that it is characterised by prolonged “warmth”, effectively representing, in this region, the longest period of persistent warm or mild SST of the past 1 Ma. This interval is also characterised by relatively subdued sea level changes, with moderate highstands during interglacial peaks and a small sea level decrease during MIS 14.

In summary, whilst many aspects of the M23414/ODP Site 980 SST record are consistent with that of other long climate records, i.e. the structure of many late Middle and Late Pleistocene warm phases, the prolonged warmth of the interval MIS 15 to 13, there are many features of this record that are very different, i.e. the strength of climate/cycles in the late Early Pleistocene, the magnitude of interglacial warmth in the early Middle Pleistocene and the strength of interstadial events in many warm stages of the past 0.45 Ma. This comparison highlights the fact that a locally specific record, rather than a “global” record, is important for understanding the precise climatic history of a region.

Long-term climate change in the northeast Atlantic and the Palaeolithic record of the British Isles

Glacial/interglacial cycles

It is widely accepted that abandonment during glacials and re-occupation during interglacials/warm stages characterises the British Palaeolithic of the past 400ka (Ashton and Lewis, 2002; Ashton et al., 2011; Pettitt and White, 2012). The SST record presented in this study shows that from MIS 12 onwards, high magnitude climate cycles were well established with the magnitude of mean annual temperature shifts from full glacial to full interglacial being in the order of around 13^{o}C. Consequently, the M23414/ODP Site 980 record provides evidence for high magnitude climate cycles during this interval which would support this pattern of human migration. Significantly, the SST record also shows that during the transition from the Early to Middle Pleistocene glacial/interglacial cycles of a magnitude and duration that was consistent with those of the late Middle and Late Pleistocene were already established by 1 Ma. This implies that the earliest known occupation event in northern Europe, the site of Happisburgh III, would have occurred against the backdrop of extreme glacial/interglacial cycles, not the more moderate 40ka cycles that are apparent in many benthic δ^{18}O records (see Parfitt et al., 2010). What adaptations would have been necessary for the successful migration into, and occupation of, northern Europe is a key research question. The SST record presented here shows that there is nothing different about the nature of glacial/interglacial forcing at this time that would make the challenges of occupying this region any different from that which later human populations would have experienced.

Climate variability at the isotopic substage level

A key characteristic of both the Palaeolithic and palaeoenvironmental record of the British late Middle Pleistocene is the evidence for "complexity" that exists within deposits of a single warm isotopic stage (White and Schreve, 2000; Candy and Schreve, 2007; Ashton et al., 2008). MIS 11 and 9, for example, both contain evidence for three distinct types of lithic industries (See White and Schreve, 2000); an early core and flake industry (the 'Clactonian') and a later Mode II industry occur in both of these warm stages. The later deposits of MIS 11 contain evidence for technological innovations (the presence of twisted ovate hand axes), whilst the later MIS 9 deposits contain the first evidence of levallois technology in northern Europe. It has been suggested that the presence of this archaeological diversity and its potential implications for the migration into Britain of different populations of early humans is a function of climate forcing during a single MIS at sub-stage level. MIS 7 sequences also contain abundant evidence for large climatic shifts with multiple temperate phases separated by evidence for significant climatic deteriorations (Schreve, 2001b; Candy and Schreve, 2007).

In the M23414/ODP Site 980 record one of the clearest features of warm stages of the past 0.45 Ma is the evidence for strong forcing at the isotopic substage level. After the main interglacial "peak" most stages contain evidence for a cooling event followed by a post-interglacial warm event. The magnitude of the cooling event is approximately half that experienced during a full interglacial/glacial shift, whilst the magnitude of the warm event is close to that of fully interglacial conditions. This latter observation is particularly significant as, in the British terrestrial record, climatic reconstructions for warm stage interstadials, such as MIS 5a at Isleworth, indicate summer temperatures comparable to, or even higher than, modern day conditions (Coope et al., 1998). The climatic framework for warm MIS of the past 0.45 Ma in the northeast Atlantic is one of strong substage forcing which would explain both the palaeoenvironmental complexity seen in stages such as MIS 5 and 7, whilst also providing a potential driver for the archaeological diversity seen in MIS 9 and 11. It is only in MIS 11 that the warming in a post-interglacial interstadial appears relatively subdued, this is consistent with the apparent absence of such an event in LR04 and the short-duration of late-MIS 11 interstadial events in EDC and multiple North Atlantic records (Lisiecki and Raymo, 2005; Jouzel et al., 2007). Candy et al. (2014) have argued that the variability of the expression of such events in different records is a combination of differences in the resolution of such records and the relatively short-duration of these interstadials. The subdued nature of the warming seen in late MIS 11 within M23414 could be a function of this as the sample resolution is ca 1.6 kyr, since the data presented in Oppo et al (1998) from Site 980 indicates several cooling-warming events during late MIS 11. Moreover, a number of authors have argued for clear but short-lived warming events in the British Isles during late MIS 11 (Schreve, 2001b; Coope and Kenward, 2007; Ashton et al., 2008; Candy et al., 2014).

Minimal cooling during MIS 15-13

With respect to early human occupation, the period MIS 15-13 is one of the most significant intervals as it is associated with; 1) a proliferation in the number of archaeological sites found in northwest Europe, and 2) the widespread adoption of Mode II technologies (Hosfield, 2011; Candy et al., 2015; and see Schreve et al. 2015 and references therein). This is not just true for the British Isles but also for much of western and central Europe north of the Alps (See Schreve et al., 2015). It is also an important interval in the SST history of the northeast Atlantic as it is a period of uniquely prolonged warmth (see Figure 6) with moderate sea level changes. The MIS 14 cold stage is the warmest of any glacial of the last 1 Ma, whilst the climatic minimum lasts for less than 9ka. North Atlantic records suggest the Arctic (or subpolar) front was further North than during MIS 16 or 12 (Alonso-Garcia et al., 2011b). Furthernore, there is no evidence for Heinrich(-like) Events in the North Atlantic during MIS 14, indicating small continental ice sheets circum the Atlantic (Hodell et al., 2008; Naafs et al., 2011; Naafs et al., 2013). Hao et al. (2015) suggest that MIS 14 was such a minor cold stage that it can be argued that, in the northern hemisphere at least, interglacial conditions persisted for in excess of 100 kyrs,. Whether this means that conditions were fully interglacial or more interstadial-like is unclear but it appears to be a period that contained minimum evidence for glacial conditions. Hao et al. (2015) have argued that these persistent warm conditions promoted favourable conditions for a second wave of hominins from Africa into Eurasia. It is, therefore, important to stress both the uniqueness of the climate of this time interval and its significance to early human occupation in northwest Europe. The slightly lower sea level (Spratt and Lisiecki, 2016; Elderfield et al., 2012), compared to other interglacials is also a factor that may have facilitated the occupation of the British Isles. Whilst sea level records (Figure 3) also indicate that this was an interval when eustatic levels were relatively low, with respect to other interglacial conditions, this does not necessarily mean that Britain was more accessible to early colonisers. The land bridge (in the region of the straits of Dover) that allowed a permanent connection between Britain and the continent persisted until MIS 12, when it was destroyed by a major glacial outburst flood (Toucanne et al., 2009). No geographical boundary to early human colonisation of Britain would, therefore, have existed during MIS 13-15 regardless of eustatic sea level.

Only two known archaeological sites, Pakefield and Happisburgh III, are known from northwest Europe prior to the MIS 13-15 interval (and Westaway (2011) has argued that both of these sites could be encompassed within the climatostratigraphy of MIS 15). The sites of Boxgrove, Waverley Wood, Brooksby, Happisburgh I, Feltwell, Westbury-sub-Mendip and High Lodge, among others, can, however, all be confidently placed in the MIS 15-13 interval (Candy et al., 2015). Consequently, whilst evidence for human occupation of this region does occur prior to MIS 15, it is during the period of prolonged warmth, MIS 15 to 13, that evidence for human occupation proliferates. The observation that the first period during which abundant evidence for human occupation in northwest Europe occurs is a period of prolonged climatic warmth is, therefore, an important one. The M23414/ODP Site 980 SST record indicates that the interglacial peaks of this interval were as strong as those that occurred from MIS 11 onwards, however, much of this period may have been more interstadial in character than fully interglacial. Candy et al. (2015) have shown that very few of the occupation events in this interval occurred during peak interglacial conditions with the palaeocology of many of these sites being late-interglacial or interstadial in character. This would fit in with the SST evidence for the climate of this interval which is indicative of a period of prolonged “warm” but not always fully interglacial conditions.

Climatostratigraphy of the early Middle Pleistocene and its significance for the age of the earliest occupation events

For the last 0.45 Ma in Britain it is routinely possible to correlate interglacial/interstadial deposits with specific marine isotope stages, for the period 0.45-0.8 Ma this is more difficult (Candy et al., 2010; Preece and Parfitt, 2012). This interval lacks the robust river terrace/raised shoreline stratigraphies that have been so important in sub-dividing the British late Middle and Late Pleistocene, whilst few radiometric dating techniques exist that can be applied to this period. Biostratigraphy and AAR have allowed the identification of biostratigraphic assemblages for the EMP, some of which can be relatively securely placed into MIS 13 and/or late MIS 15 (Penkman et al., 2011; Preece and Parfitt, 2012; Candy et al., 2015). However, a number of older biostratigraphic groups exist. On the basis of biostratigraphy these must be older than MIS 13 but, in light of the fact that none of deposits that these fossil assemblages occur within have reversed magnetisation, they must be younger than 0.78Ma.

Two observations are crucial here. Firstly that Preece and Parfitt (2012) suggest the existence of five discrete biotsratigraphic assemblages that correlate to fully temperate episodes within the period 0.45-0.78 Ma. Secondly, that there is a suggestion, which appears robust, that MIS 19 is not represented in the British sequence because the early/middle part of this interglacial should be magnetically reversed and this has yet to be observed within any British temperate-stage deposit (Candy et al., 2015). The five different biostratigraphic groups identified by Preece and Parfitt (2012) must, therefore, be resolved within three warm MIS. This situation is further complicated by the fact that two interglacial sequences, Pakefield and West Runton, that must, on the basis of bistratigraphy and prevailing palaeoclimate, be distinct temperate episodes (Stuart and Lister, 2001; Preece and Parfitt, 2012) have very similar AAR values, implying that they accumulated during the same MIS (Penkman et al., 2011).

The M23414/ODP Site 980 record is an important first step in the resolution of these inconsistencies, as it highlights the climatic complexity of warm stages of the EMP, such as MIS 15. This warm stage contains at least three temperate substages that appear, in terms of temperature regime, to be fully interglacial. Furthermore, these substages are each separated by some 20ka, and are, therefore, sufficiently chronologically distinct from one another to allow for biostratigraphic differences to exist between the flora and fauna of each substage. The climatic structure of MIS 15 is, therefore, compatible with the existence of two biostratigraphically and climatically distinct interglacials that are indistinguishable on the basis of AAR values.

Previously, it had been proposed that Pakefield and West Runton occurred in distinct MIS with Pakefield correlating to either MIS 19 or 17 (Stuart and Lister, 2001; Parfitt et al., 2005; Candy et al., 2015). The suggestion that the deposits at Pakefield correlate to MIS 19 has always been debated as the Brunhes/Matuyama boundary occurs in the middle of this interglacial and yet despite the deposits at Pakefield recording a major part of a temperate stage all of the sediment units exhibit normal magnetic properties. The correlation of the Pakefield sequence with MIS 17 is questioned here on the basis of the SST record of this interglacial seen in Site 980. The palaeoecological assemblage from Pakefield has been used to reconstruct one of the warmest interglacial climates known to have occurred in the British Isles with summer temperatures at least 3-4°C warmer than the present day (Parfitt et al., 2005; Candy et al., 2006; 2010; Coope, 2006; 2010), however, in Site 980 the SST values of MIS 17 are the coldest of any interglacial of the past 1 Ma. It is, therefore, considered unlikely that the enhanced warmth recorded at Pakefield is compatible with the cool SST regime in the immediate northeast Atlantic. In this context the proposed correlation of Pakefield with MIS 15, which contains intervals of high SST values in Site 980, seems reasonable.

If it is accepted that the climatic complexity of MIS 15, recorded in Site 980, can account for biostratigraphically distinct sequences, such as West Runton and Pakefield, to have accumulated during a single MIS it has major implications for the earliest human occupation of northwest Europe. On the basis of the presence of archaic small mammal species present in the Pakefield sequence (Parfitt et al., 2005) this site is the second oldest, after Happisburgh III, of all of the Palaeolithic sites in northwest Europe (Parfitt et al., 2010). This implies that, with the exception of Happisburgh III, all of the early (pre-MIS 12 or pre-Anglian) archaeological sites in Britain must correlate with the prolonged warm interval represented by MIS 15 to 13 (Candy et al., 2015). This unique climatic period, therefore, becomes of increasing importance to our understanding of early human occupation in this region as it would appear that the first major proliferation of archaeological evidence occurred during a 100 kyr period dominated by interglacial and interstadial conditions.

Conclusions

Sea surface temperature data from M23414/ODP Site 980 has been used to investigate the evolution of climates in the region of the British Isles for the past 1 Ma, with the particular aim of understanding the climatic background to early human occupation in northwest Europe. The correlation between this SST record and the British Palaeolithic record allows the following conclusions to be drawn. Firstly, that by the time of the earliest known occupation of Britain the extreme 100ka glacial/interglacial cycles that characterise the late Middle and Late Pleistocene had already become established. The magnitude and frequency of the climate cycles that this earliest colonisation occurred in the context of would, therefore, have been no different to glacial/interglacial cycles of the Late Pleistocene. Secondly, that the archaeological complexity that is observable in many warm isotopic stages is mirrored by climatic complexity. During the late Middle and Late Pleistocene the occurrence of large scale stadial/interstadial climatic oscillations after the main interglacial peak of many warm stages, meaning that archaeological complexity occurs is routinely found against a backdrop of strong climate forcing. Finally, the time interval during which the first major proliferation of early archaeological evidence occurs in Britain, MIS 15 to 13, is found in association with a period of prolonged warmth which is unique in the climate history of the past 1 Ma years in this region. Most of this time interval is characterised by interglacial to interstadial conditions with the glacial interval of MIS 14 being short-lived and subdued and it is under these conditions that the first widespread colonisation of Britain and northern Europe appears to have occurred.

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Figures

Figure 1 – A comparison between the LR04 stacked benthic $\delta^{18}O$ record and the British Palaeolithic record. Two possible time periods are shown for Pakefield and Happisburgh II as the absolute age of these sites is not clear (see Parfitt et al., 2005; 2010 and Westaway, 2011 for discussion). Candy et al. (2015) have argued that the first appearance of Mode II archaeology is during MIS 13 or, at the earliest, late MIS 15. The major climatic events/tranisitions during this epriod are shown below the benthic record.

Figure 2 – Map showing the locations of the key marine records and, inset, British terrestrial sites discusse din the text (WR = West Runton, Hp = Happisburgh, Pk = Pakefield, Is = Isleworth, Bx = Boxgrove, W-S-M = Westbury-sub-Mendip, WW = Waverley Wood, Br =- Brooksby, HL = High Lodge, F = Feltwell).

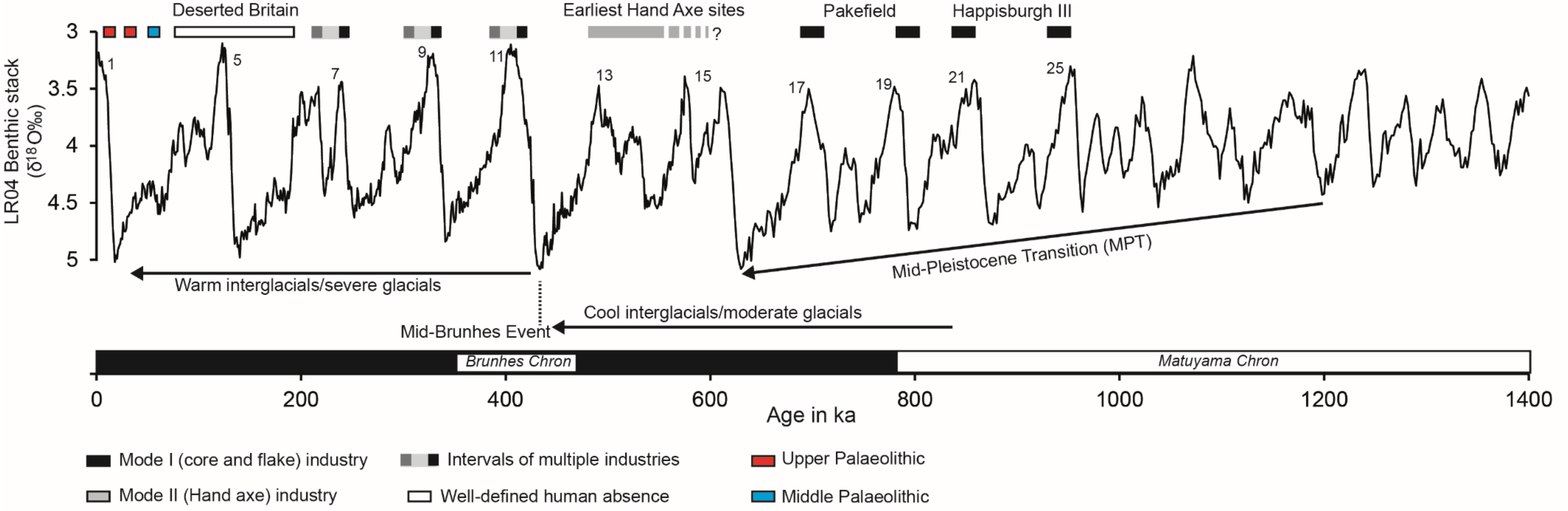
Figure 3 – A comparison of the M23414/ODP Site 980 mean annual SST record (a) calculated in this study using the original foraminifera data and the MAT technique (MARGO dataset), with: (b) the sea level record of Site IODP 1123 (Elderfield et al., 2012) and the sea level stack SL16 (Spratt and Lisiecki, 2016), (c) LR04 benthic stack (Lisiecki and Raymo, 2005) and (d) the EDC temperature anomaly record (Jouzel et al., 2007).

Figure 4 – Comparison of modern (a) and Pleistocene (b) sea surface temperature characteristics of sites M23414 (black) and ODP Site 980 (grey). Both the modern winter and summer temperature values and the reconstructions for sea surface temperature values during MIS 5e show that the sites have similar climatic contexts and are, therefore, suitabel for the production of a combined SST record. Modern temperature data from WOA13, MIS 5e data recalculated for this study from Kandiano and Bauch (2003) and Oppo et al. (2006).

Figure 5 – Detailed comparison between SST (mean annual) data from M23414 (MIS 5-11) and ODP Site 980 (MIS 15 to 25) with LR04. MIS 13 shows a composite SST record from M23414, U1314 and ODP 980. A comparison with the EDC temperature anomaly record is also made for MIS 5-19 where such data is available.

Figure 6 – SST recod of MIS 15 to 13 in the M23414/U1314/ODP Site 980 record and its relationship to the earliest Palaeolithic sites (see Candy et al., 2015 and text for discussion).

Figure 1



Deserted Britain
Earliest Hand Axe sites
Pakefield
Happisburgh III
?
LR04 Benthic stack ($\delta^{18}O$‰)
3
3.5
4
4.5
5
1
5
7
9
11
13
15
17
19
21
25
Warm interglacials/severe glacials
Mid-Pleistocene Transition (MPT)
Cool interglacials/moderate glacials
Mid-Brunhes Event
Brunhes Chron
Matuyama Chron
0
200
400
600
800
1000
1200
1400
Age in ka
Mode I (core and flake) industry
Intervals of multiple industries
Upper Palaeolithic
Mode II (Hand axe) industry
Well-defined human absence
Middle Palaeolithic

Figure 2

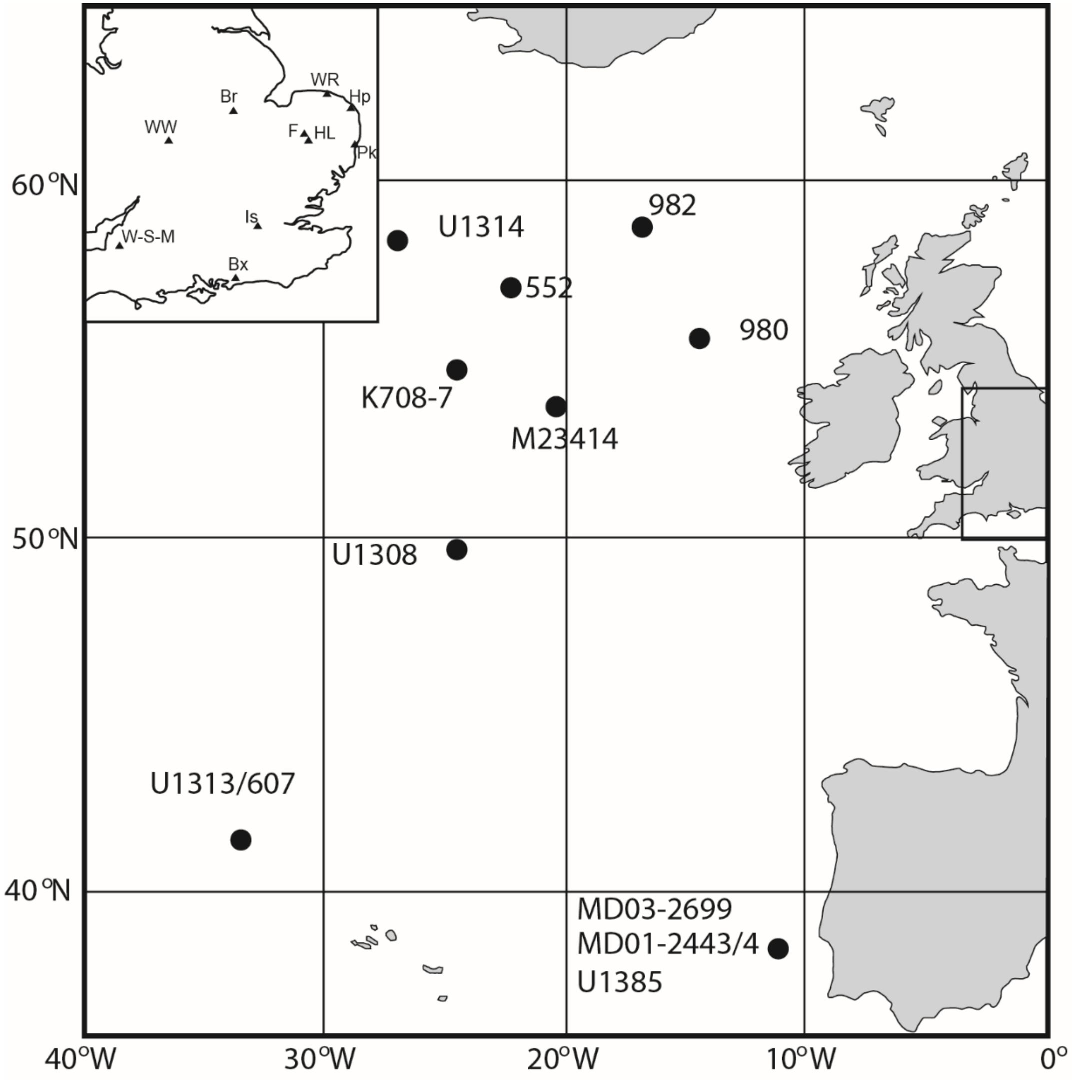

WR
Br
Hp
WW
F
HL
Pk
Is
W-S-M
Bx
60 °N
982
U1314
552
980
K708-7
M23414
50 °N
U1308
U1313/607
40 °N
MD03-2699
MD01-2443/4
U1385
40°W
30°W
20°W
10°W
0°

Figure 3

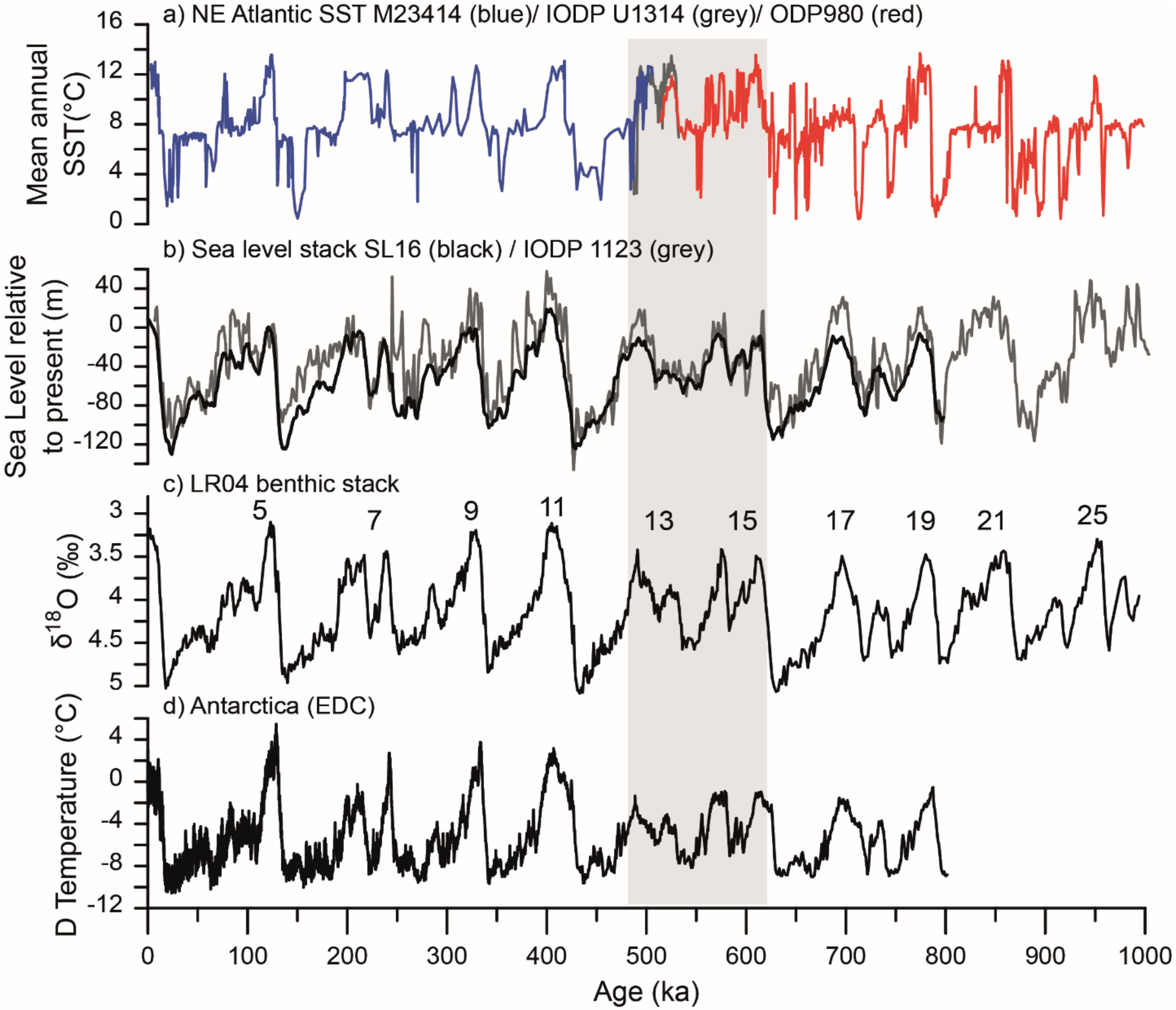
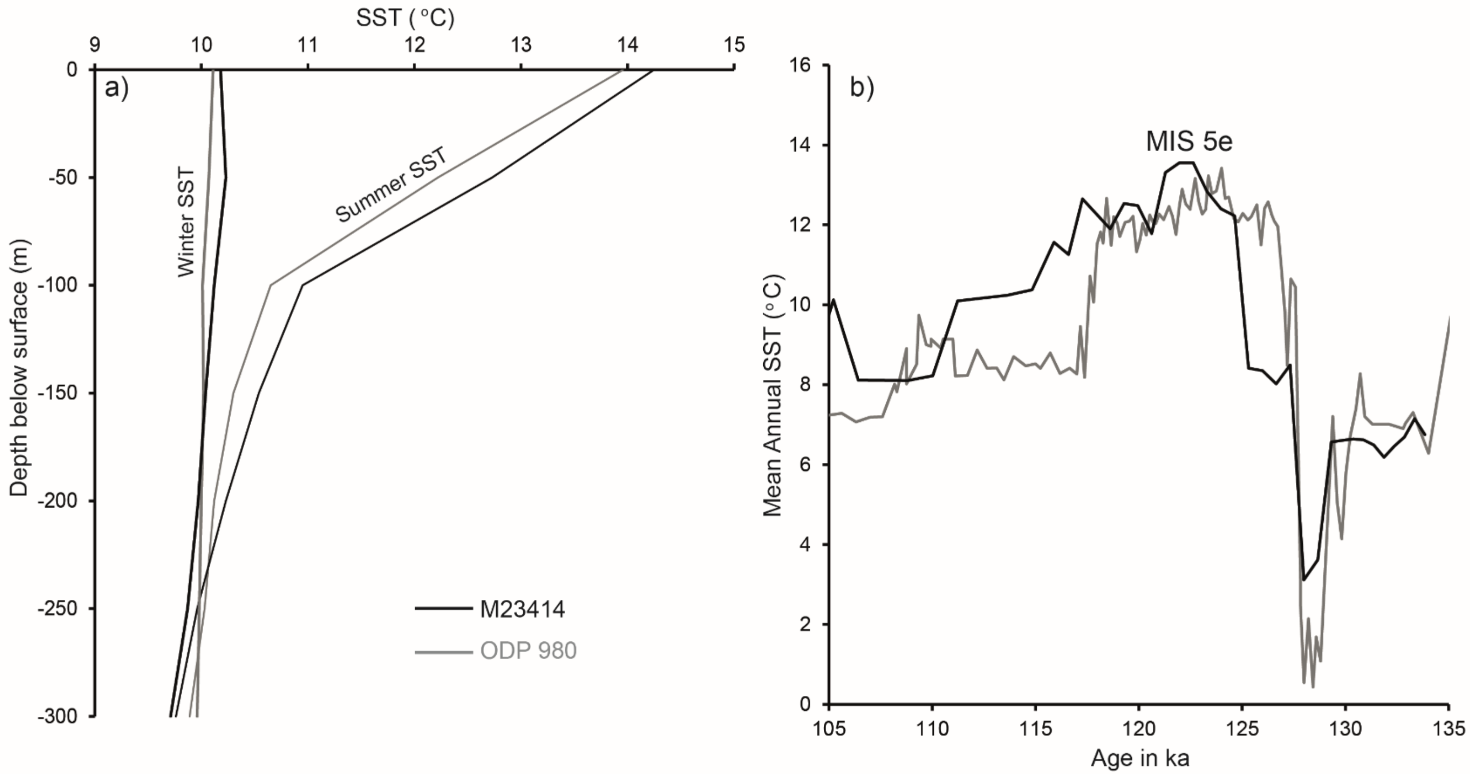
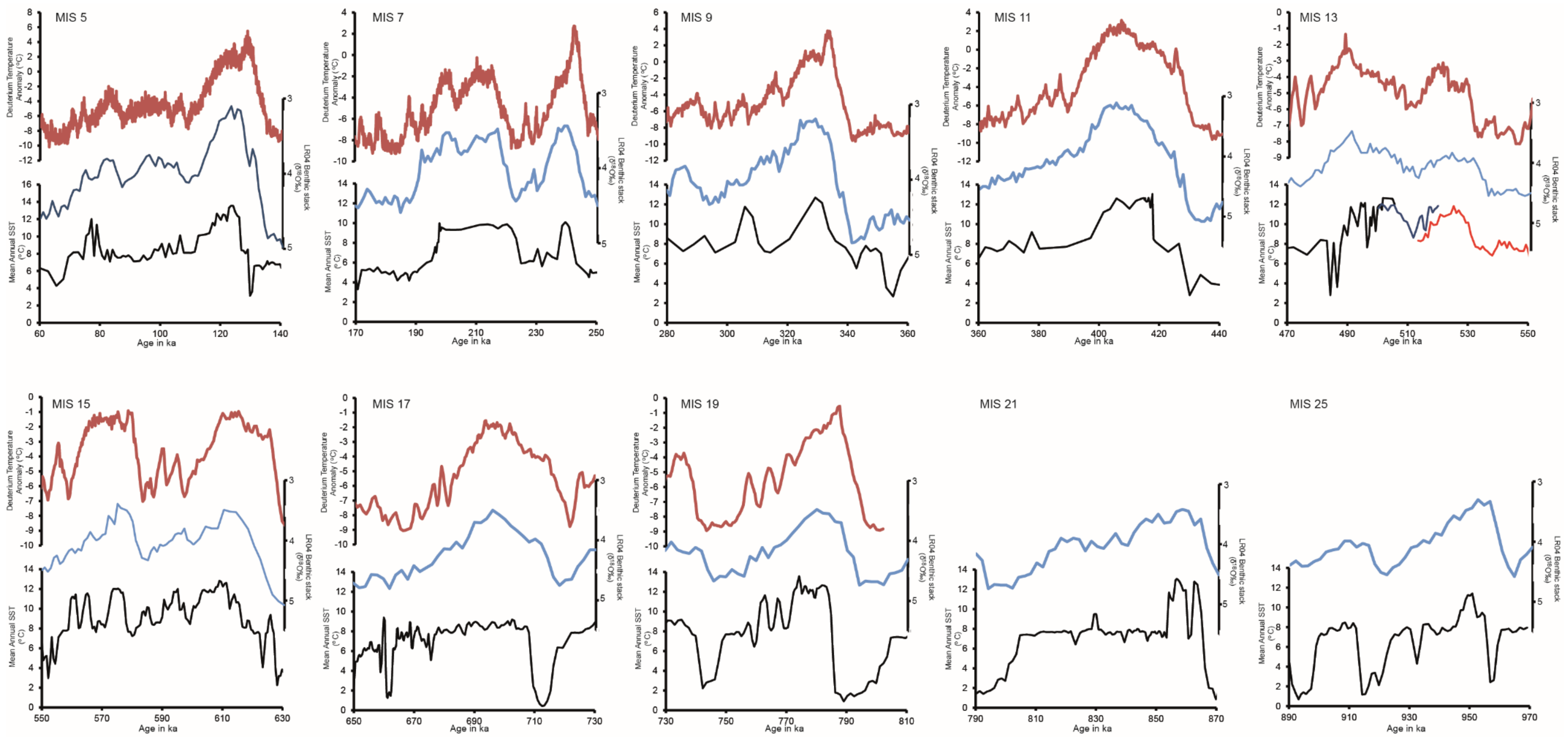

a) NE Atlantic SST M23414 (blue)/ IODP U1314 (grey)/ ODP980 (red)
Mean annual SST(°C)
16
12
8
4
0
b) Sea level stack SL16 (black) / IODP 1123 (grey)
Sea Level relative to present (m)
40
0
-40
-80
-120
c) LR04 benthic stack
δ18O (‰)
3
3.5
4
4.5
5
5
7
9
11
13
15
17
19
21
25
d) Antarctica (EDC)
D Temperature (°C)
4
0
-4
-8
-12
0
100
200
300
400
500
600
700
800
900
1000
Age (ka)

Figure 4



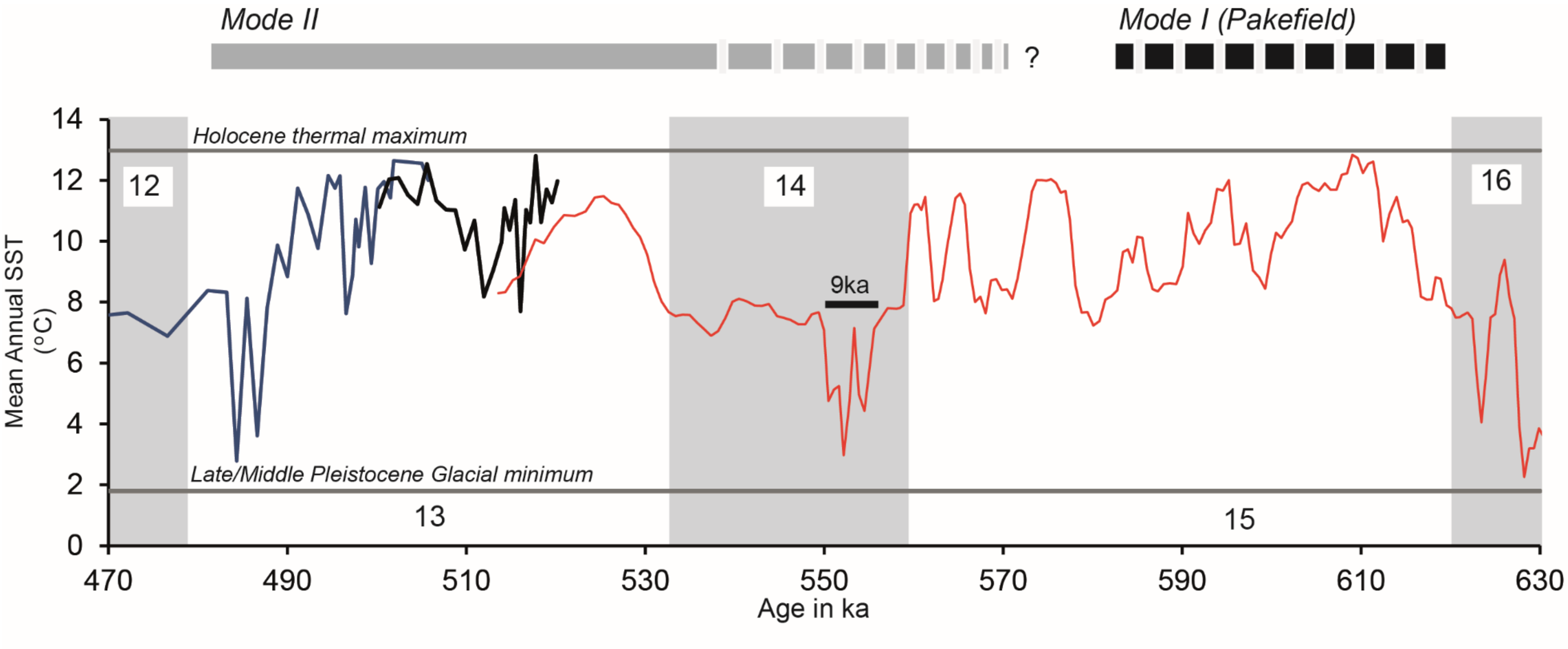
SST (°C)
a)
Winter SST
Summer SST
Depth below surface (m)
M23414
ODP 980
b)
MIS 5e
Mean Annual SST (°C)
Age in ka

Figure 5



MIS 5
MIS 7
MIS 9
MIS 11
MIS 13
MIS 15
MIS 17
MIS 19
MIS 21
MIS 25
Deuterium Temperature Anomaly (°C)
Mean Annual SST (°C)
LR04 Benthic stack (δ18O‰)
Age in ka

Figure 6


Mode II
?
Mode I (Pakefield)
Holocene thermal maximum
12
14
16
9ka
Late/Middle Pleistocene Glacial minimum
13
15
Mean Annual SST (°C)
14
12
10
8
6
4
2
0
470
490
510
530
550
570
590
610
630
Age in ka